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HEARING RISK TO WEARERS OF CIRCUMAURAL HEADPHONES: an investigation

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Summary

Exposure to high sound levels can cause damage to the auditory system, either gradually over a period of time, or, in the case of very intense sounds, instantaneously. Particular care is therefore required in the use of headphones, which are capable of generating much higher effective sound levels than loudspeakers.

This report summarises the results of a series of tests which show that headphone wearers tend to listen at significantly higher levels than loudspeaker users.

A rudimentary artificial ear is described which enables a standard sound level meter to be used with reasonable accuracy for the measurement of headphone sensitivities.

Finally, various methods are recommended of safeguarding the hearing of headphone wearers.

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1. Introduction

It has long been recognised[1,2] that exposure to high-intensity sound can cause irreversible loss of hearing acuity. Two forms of damage can occur: firstly, very intense sounds (sound levels higher than about 150 dBA) can cause instantaneous damage to the auditory mechanism and secondly, prolonged exposure to sounds of lower intensity (90 dBA and above) can cause progressive hearing loss. The significant factor in the latter appears to be the total amount of acoustic energy to which the subject is exposed.

Many types of monitoring loudspeaker can generate sound pressure levels high enough to cause significant hearing loss over the period of a working lifetime, and, within the BBC, warning notices have been introduced to remind operators of possible hazard. No loudspeaker in either current or projected use is even nearly capable of causing instantaneous hearing damage under normal listening conditions.

The use of headphones presents somewhat different problems. If (as has happened in the past) a pair of low-impedance headphones is used with a powerful loudspeaker amplifier, sound levels high enough to cause instantaneous hearing damage may be generated. This hazard may readily be avoided by permitting the use only of a suitable type of headphone amplifier. However, for two reasons, the risk of long-term hearing loss may be greater than that incurred with loudspeakers. Firstly, it can be shown that most subjects appear to choose an appreciably higher listening level on headphones than on loudspeakers. Secondly, a headphone wearer may choose as high a listening level as he likes without disturbing or even attracting the attention of anyone else.

This Report presents the results of a series of subjective tests showing the subjects' preference for higher listening levels on headphones than on loudspeakers. The problems in measuring effective sound pressure levels under headphones are outlined and a rudimentary artificial ear is described which enables an approximate estimate of these levels to be obtained.

2. Measurements relating to hearing risk

2.1 Equivalent continuous sound level[3]

The probability of hearing loss appears to depend on the total amount of acoustic energy to which the subject is exposed. It is generally believed that the maximum sound level to which anyone should be exposed for the duration of a working lifetime (nominally taken as 40 hours per week for 40 years) is 90 dB(A). For each 3 dB in excess of this level, the period of exposure should be halved (e.g. 8 hours per day at 90 dB(A), 2 hours per day at 96 dB(A)). As most sources of sound or noise fluctuate in level, it is convenient to define an equivalent continuous sound level by the expression:

$$L_{eq} = 10 \log_{10} \frac{I}{T} \int_0^T \frac{P(t)^2}{P_0^{\,2}} \, dt$$

where T is the duration of exposure,

$P(t)$ is the instantaneous sound pressure (A-weighted) at a time (t)

and P_0 is the standard reference pressure (20μPa).

By means of an integrating noise dosemeter, of which several types are commercially available, both L_{eq} and duration of exposure may be measured directly.[3] It is in terms of L_{eq} that most legislation on noise exposure is written.

2.2 Relationship between sound pressure under headphones and the equivalent ambient sound pressure

Most hearing damage is industrial in origin, and most published work therefore relates to ambient sound levels measured either near the observer or in his absence. Since the use of headphones inevitably requires a monitoring point much closer to the ear than normal, it was necessary to develop a technique which relates measurements taken at the entrance of the ear canal to ambient L_{eq} measurements.

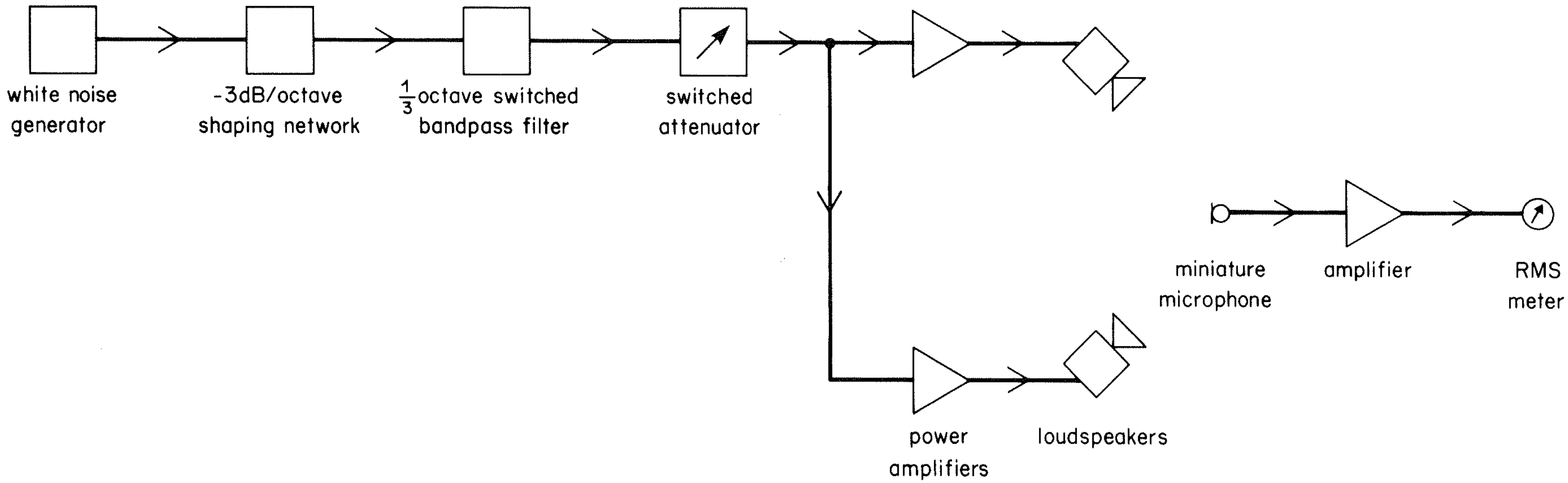

Fig. 1 - Arrangement for comparing SPL in ear canal with ambient SPL

The ratio of ambient sound pressure to resultant sound pressure at the entrance to the ear canal was measured for all test subjects using the arrangement shown in Fig. 1. Initially, the measuring microphone was set up in the listener's absence and the loudspeakers driven with a frequency sweep. However, due to room modes, the sound pressure at the point of measurement fluctuated very sharply with frequency; to average out these variations, third-octave bands of noise were used instead. For this purpose, the output of a white-noise generator was shaped with a suitable network at − 3 dB per octave to obtain "pink" noise which has equal energy in each third octave band. In the absence of a listener the attenuator settings required to produce equal sound pressure levels (SPL) in each band at the listener's position were noted. The listener was then introduced into the room, the miniature microphone was placed at the entrance to his ear canal, and the bands of noise were reproduced using the attenuator settings previously noted. This was done for each subject in turn, and the resultant SPL at the entrance to the ear canal was measured for each frequency band. Fig. 2 shows the miniature electret microphone which was used for this purpose. The results of the measurements, averaged for all subjects, are shown in Fig. 3. At frequencies below 5 kHz the measurements varied by less than 2 dB from person to person; above this frequency variations were considerable with standard deviations of up to 5 dB. However, the response of most headphones falls off rapidly above 5 kHz as does the energy content of much programme material; it is therefore considered that the curve of Fig. 3 is applicable with reasonable accuracy to any listener.

Fig. 2 - Miniature electret microphone used to measure sound pressure in ear

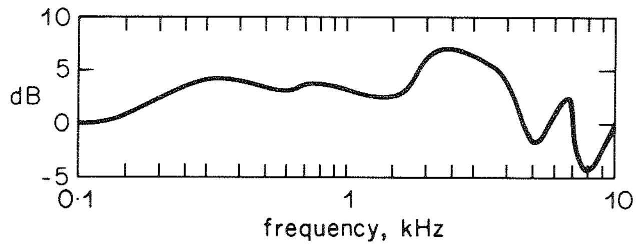

Fig. 3 - Ratio of sound pressure at entrance of ear canal to diffuse-field pressure in absence of listener (Average for 18 subjects)

By making use of the relationship of Fig. 3, it is possible to estimate the equivalent ambient L_{eq} to which a headphone wearer is subjected while he listens to a given piece of programme material. The measuring arrangement is shown in Fig. 4; correction for the difference between ear-canal and ambient SPL is made by setting a graphic equaliser to the inverse curve of Fig. 3.

3. Subjective tests to determine listening – level preferences and tolerances

Two series of subjective tests were carried out, one with headphones (Fig. 4) and the other with loudspeakers (Fig. 5). The tests were carried out in an acoustically treated room whose reverberation time is comparable to that of a typical domestic listening room (Fig. 6). Subjects were presented with five short programme excerpts and were asked to set listening levels to comply, in turn, with the following criteria:

(1) "Normal" – a comfortable level for critical listening.

(2) "Loud" – the highest level tolerable without discomfort or fatigue for the duration of the test.

The five programme excerpts, of widely varied musical content, are listed in Table 1. To test the system, and provide a check on subjects' consistency, a trial run was made using headphones only on Item A. The final test schedule for each participant was as follows:

Series 1 – Headphones

Audiometric test

All five items, random order, each first "normal" then "loud".

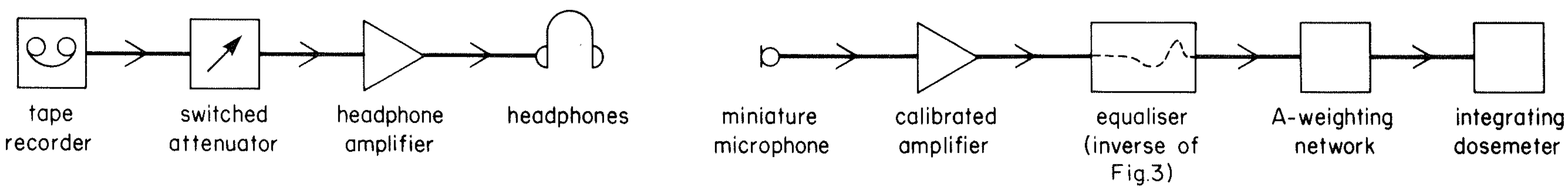

Fig. 4 - Arrangement for subjective tests with headphones

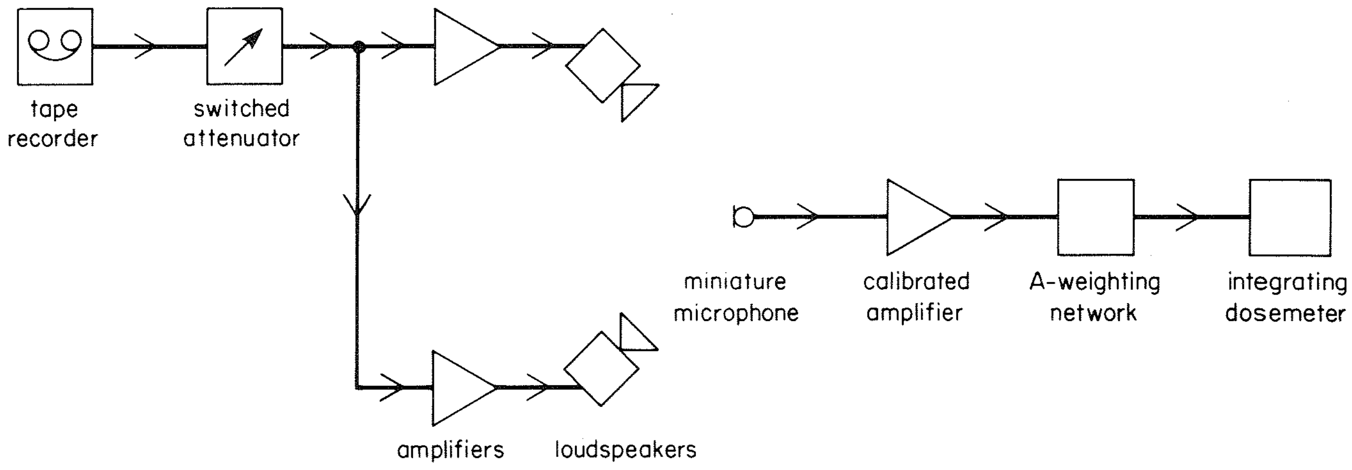

Fig. 5 - Arrangement for subjective tests with loudspeakers

Series 2 — Loudspeakers

Audiometric test

All five items, random order, each first "normal" then "loud".

TABLE 1

Music from which the five excerpts were taken.

A	"Bad bad boy": heavy rock (Nazareth)
B	"Ob-la-di": calypso (Marmalade)
C	Mars: Planet suite (Holst)
D	Fourth movement: Pathétique (Tchaikowsky)
E	"Brazil": Latin-American (Radio orchestra)

To reduce the probability of hearing threshold shift, which can be caused by prolonged listening at high level, it was arranged that no subject underwent both series of tests on the same day. The inclusion of an audiometric test before each series ensured that all subjects' hearing was normal, and enabled any temporary shifts to be detected (as an example, one participant suffered temporary impairment at mid frequencies due to the common cold, and his tests were consequently postponed until his recovery).

A total of eighteen subjects, mostly male, took part in the tests. About half of these are accustomed to critical listening tests as part of their everyday work.

As a final check, a few tests were made with a different type of headphone to see whether the trends observed in the main tests would be repeated. Both types of headphones are in very common use in the broadcasting service.

TABLE 2

Loudness levels (L_{eq}) chosen for the five excerpts (mean for all subjects).

Sound Source	Level	Musical Excerpt					
		A	B	C	D	E	Mean
Headphones	Normal	91.2	90.8	87.8	89.4	91.9	90.2
	Loud	100.4	98.5	95.4	97.1	98.9	98.1
Loudspeakers	Normal	81.4	84.9	83.4	85.2	82.7	83.5
	Loud	90.1	91.7	89.8	91.5	89.4	90.5

TABLE 3

	Level	Musical Excerpt					
		A	B	C	D	E	Mean
ΔL_{eq}	Normal	10.6	6.1	4.5	5.4	9.2	7.2
Standard Deviation (dB)		3.8	3.9	3.1	2.3	4.3	4.2
ΔL_{eq}	Loud	10.2	7.1	5.7	6.2	9.0	7.6
Standard Deviation (dB)		4.7	5.0	3.8	4.5	4.5	4.7

Amount ΔL_{eq} by which levels chosen for headphones exceed those for loudspeakers.

4. Discussion of results

4.1 Absolute listening levels

The absolute listening levels are shown in Table 2, averaged for all subjects. Several features of the results deserve comment.

Although only the results of the two main test series are shown, it is worth recording that the results of the initial trial run (Item A on headphones) were very close indeed to those obtained for the same passage in Series 1. Most subjects were consistent to within 2 dB in their choice of level, and the maximum inconsistency for any subject was 4 dB.

The standard deviations of all the results in Table 2 were around 5 dB so that the variations within each row probably have no significance. There appears, therefore, to be no obvious correlation between absolute listening levels and programme content. It is however, known that studio managers who mix pop or light music on loudspeakers tend to listen at much higher levels than those who mix serious music. It is therefore likely that an individual's choice of listening level depends on both his immediate professional involvement and on the type of work that he normally does, and that hearing risk can be assessed only by measurements in situ.

"Specialist" listeners (i.e. those accustomed to critical listening) did not choose levels appreciably different to those of non-specialists, nor were their results noticeably more consistent.

It is clear that in all cases, subjects choose to listen at higher levels with headphones than with loudspeakers. This difference is of sufficient magnitude and consistency to outweigh any statistical fluctuations in the results.

The amount by which "loud" exceeds "normal" is about the same for headphones as for loudspeakers. This suggests that whatever the aspect of auditory perception that makes ambient sound appear louder than sound in headphones, it is not strongly level-dependent.

4.2 Relative listening levels

The difference ΔL_{eq} in chosen listening level between headphones and loudspeakers was computed for each subject and for each programme item, i.e. each test result of Series 2 was subtracted from the corresponding result of Series 1. These differences were then averaged for all subjects, and are shown with their standard deviations in Table 3. As before, some points are worthy of comment.

Inspection of Table 3 shows that ΔL_{eq} may depend upon programme content: the rows of "normal" and "loud" figures show a similar pattern, which in view of the small standard deviations, is unlikely to be due to chance. It is noteworthy that the highest values of ΔL_{eq} occur for the pop and Latin-American excerpts, all of which have a much lower peak-to-mean energy ratio than the serious music. Thus the type of programme material which seems to encourage headphone wearers to listen at relatively high levels is also that which is most likely to cause hearing damage.

The values of ΔL_{eq} chosen by "specialist" listeners did not differ noticeably from those chosen by non-specialists, nor were they more consistent.

The brief experiments carried out with head-

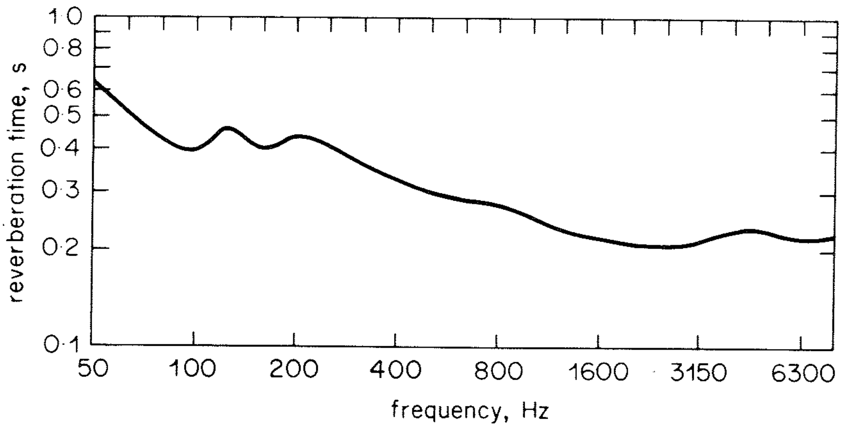

Fig. 6 - Reverberation time of room used for subjective tests

phones of a different type indicated that very similar results would have been obtained with these.

4.3 Practical implications of test results

The tests described above are by no means exhaustive. For instance, the test period was too short to investigate whether the preferred level of reproduction drifted, either up or down, with duration of exposure. They nevertheless enable some useful conclusions to be drawn.

Firstly, headphone wearers typically seem to listen at levels which are effectively 7 or 8 dB higher than they would choose if using loudspeakers. A 7 dB increase in SPL means that for the same contribution towards hearing risk, the listening time should be decreased by a factor of 5.

Secondly, although headphone wearers appear always to listen at higher effective levels than loudspeaker users, they do so particularly to programme material of high energy content, thereby compounding the risk of hearing damage.

5. Measurement of headphone sensitivites

For the purposes of the work described in this Report headphone sound levels were measured by means of a miniature microphone placed in the pinna at the entrance to the ear canal (Fig. 2). For general headphone testing, it would be useful to have available a standard artificial ear with acoustic properties approximating to those of the typical human ear. This would enable tests to be carried out under standard conditions without discomfort or risk of hearing damage.

Types of artificial ear currently available model the eardrum and part of the auditory meatus, but not the pinna;[4,5,6] these are intended for the testing of insert earphones. Thus even for testing supra-aural headphones the accuracy of these devices is open to question, and for circumaural headphones they are in their present form completely unsuitable.

A series of experiments has been described elsewhere[7] in which an IEC standard artificial ear[4] has been fitted with a simulated pinna made of suitable lossy material. Although the results as described appear promising, much more research would be required to finalise the design of an accurate artificial ear which could be reliably manufactured from specifiable materials. The work involved would be justifiable only if accurate headphone measurements were to become a routine procedure.

For approximate measurement of headphone sensitivies, a rudimentary artificial ear has been constructed; it consists simply of a wooden cradle made to fit a Bruel and Kjaer sound level meter so that the microphone appears flush with a flat surface (Fig. 7). A neoprene sheet is used to

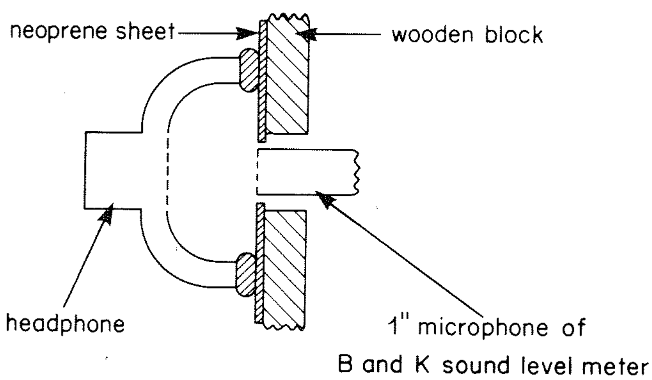

Fig. 7 - Rudimentary artificial ear for approximate measurement of headphone sensitivity

obtain a reasonably airtight seal around the microphone, and the headphone is clamped in position as shown. Using one type of headphone only, L_{eq} values obtained with this device were within ±0.5 dB of those measured using a real ear. It is suggested that measurements made on headphones of different types should in general be accurate to ±2 dB. Use of a standard artificial ear as supplied with a metal adaptor plate does not result in significantly more accurate estimates because it, too, lacks a realistic representation of a pinna.

6. Conclusions and recommendations

It has been shown that the use of headphones results in higher effective listening levels than the use of loudspeakers, the difference in L_{eq} being between 5 and 10 dB(A). It is therefore important to consider the practical problems of what can be done to safeguard the hearing of headphone wearers.

The most obvious step is to prohibit the use of loudspeaker amplifiers to drive headphones and to ensure by suitable choice of connectors that it cannot occur accidentally. This should at least prevent the generation of sound levels high enough to cause instantaneous injury.

The use of a suitable headphone amplifier does not, however, provide a general solution to the problem of long-term hearing risk. Headphones of different types vary greatly in sensitivity: for example, the two types used in the subjective tests differed by about 16 dB. Variations between headphone types could be overcome by installing an attenuator in the connecting plug of each individual pair, or by limiting the number of permitted types and using a multipin connector with different wiring for each type.

Differences in sensitivity between headphone pairs of the same type present a more difficult problem. A current DIN standard[8] states that between the left and right headphones of a pair, sensitivity should not differ by more than 2 dB. This suggests that variations of greater than 2 dB are likely to occur between different pairs of the same type. However, the probability of hearing damage appears in any case to vary considerably from one individual to another[1], so it would seem reasonable, at least in the first instance, to neglect possible differences between nominally identical pairs of headphones, and to set a maximum achievable sound pressure level appreciably below that at which long-term hearing damage is likely to occur.

Finally, a rudimentary technique for making measurements on circumaural and supra-aural headphones has been shown to give reasonably accurate results. This will have to suffice until a suitable standard artificial ear is available.

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